

THEORY OF ETA PHOTO- AND ELECTROPRODUCTION*

NIMAI C. MUKHOPADHYAY, J. -F. ZHANG

*Department of Physics, Applied Physics and Astronomy
Rensselaer Polytechnic Institute, Troy, NY 12180-3590, U.S.A.*

M. BENMERROUCHE

*Saskatchewan Accelerator Laboratory, University of Saskatchewan
Saskatoon, Canada SK S7N 5C6*

We analyze the available data on eta photo- and electroproduction, around $W \approx 1535 \text{ MeV}$, in the framework of the effective Lagrangian approach, and extract, in a nearly model-independent fashion, the electrostrong amplitude for the $\gamma N \rightarrow N^*(1535) \rightarrow N\eta$ processes. Quark model approaches are shown to be *quite inadequate* to explain this property at *all* Q^2 . In particular, at *high* Q^2 , the extracted amplitude falls *much slower* than the predictions of the quark model, as a function of Q^2 , a situation similar to the electroexcitation and decay of $\Delta(1232)$. A QCD explanation of these observations is urgently needed.

1 Introduction

Nathan Isgur, in his introductory talk¹, has emphasized the importance of studying baryons in the overall context of studying QCD: baryons are among the basic asymptotic states of QCD, having manifest non-Abelian physics and being essential in our attempt to understand nuclear physics in the QCD context. While QCD is a theory of quarks and gluons, quark models are attempts to use the effective degrees of freedom of valence quarks, with remarkable relationships to the quenched approximation on the lattice². Thus, rigorous tests of quark models are useful towards our understanding of QCD. Our work reported here should aid in this effort by providing one piece of important physics: that of the electromagnetic excitation of the $N^*(1535)$ resonance and its strong decay to the $N\eta$ channel. The processes^{3,4,5,6,7,8,9}

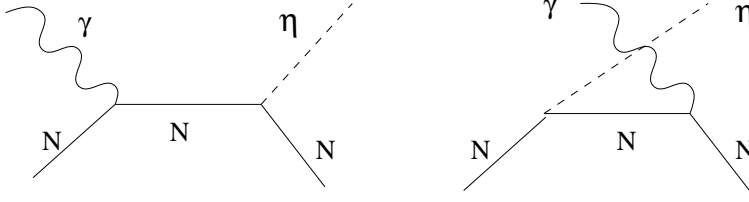
$$\gamma + p \rightarrow p + \eta, \quad (1)$$

$$\gamma + n \rightarrow n + \eta, \quad (2)$$

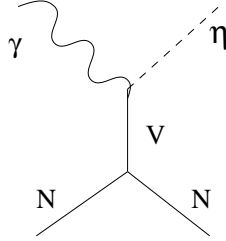
where the photon γ is real or virtual, are powerful tools to study the $N^*(1535)$ resonance, due to the special property of $N^*(1535)$ coupling strongly to the $N\eta$ channel (N , nucleon), as opposed to many other N^* 's which do not have significant couplings to this channel¹⁰. We shall use an effective Lagrangian approach (ELA), with the usual Born terms, vector meson exchanges and N^* excitations³[Fig.1], and treat the existing cross section^{5,8,9} and polarization data⁶. Our output of these analyses will be

Presented by Nimai C. Mukhopadhyay. Invited talk at the CEBAF/INT Workshop on N^ Physics, Sept. 9-13, 1996.

(a). (b). Nucleon Born terms



(c). The t-channel vector meson exchange



(d), (e) The s- and u- channel nucleon resonance excitations

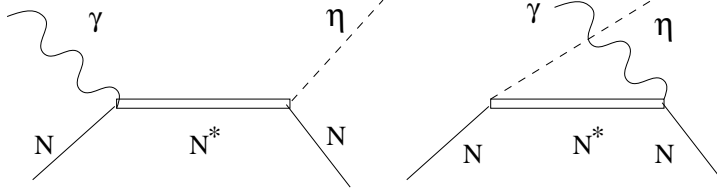


Figure 1. Mechanisms of Photo- and electroproduction of eta mesons in our approach³

a physical (dressed) parameter for the excitation of the $N^*(1535)$ resonance and its decay as a function of Q^2 , negative of the momentum transfer squared. In comparing with other calculations, only dressed or physical parameters need be compared. As discussed in the classical text on quantum electrodynamics¹¹, the relation between “bare” and physical (or “dressed”) parameters is always model-dependent¹².

We recall at the outset that the quark shell model and lattice gauge calculations agree surprisingly well in the case of the $\gamma N \rightarrow \Delta$ transition. The magnetic dipole amplitude (M1) that is extracted¹³ from the data (old or new)¹⁴ is about 285 to 290 units, while the quark model¹⁵ or the lattice calculation² is about 210 units (see Table I). Thus, there seems to be a significant transition magnetism shortage in these calculations. Could it be due to the $q\bar{q}$ pair effects, discussed by Isgur¹? We will see in the future investigations. Suffice to say that this magnetism shortage is confirmed by the Compton scattering as well¹⁶. At high Q^2 , the data seem to scale and even show

Table 1. A summary of the $N \rightarrow \Delta$ magnetic dipole amplitude (in conventional units)

Method	Authors	Result
K-matrix residue	Davidson, Mukhopadhyay ¹³	290 ± 13
ELA fits	Davidson, Mukhopadhyay and Wittman ¹³	285 ± 37
Quark model	Koniuk et al. ¹⁵	206
Lattice	Leinweber, Draper and Woloshyn ²	210 ± 25

hints of $\log s$ ¹⁷, a situation *very different* from the quark model anticipations. Even in the model of Salme *et al.*¹⁵, it would be difficult to reproduce all these features.

Remainder of this paper will be the following: in the next section, we survey the current literature to provide a quick review of the current excitements on $N^*(1535)$. Section 3 contains an overview of the ELA. Section 4 gives our basic results of the ELA for photoproduction. Section 5 does the same for electroproduction. Section 6 summarizes our conclusions.

2 Some recent excitements on $N^*(1535)$

On the experimental side, we have seen at this workshop the beautiful high quality data on eta photoproduction from Mainz in Krusche's talk⁵. Other new data⁵ from Bates and Bonn do not compare in quality with these ones. Some new polarization data⁷ are also coming from Bonn and GRAAL, but we still have to use the old data base⁶. For electroproduction of the eta mesons, the cross section data are all old⁹, except for one set coming from the Elan collaboration¹⁸ at the ELSA ring, at $Q^2 = 0.056 GeV^2$. However, these recent data show rather strange angular distributions.

On the theory side, the first recent examinations of the ELA were done by the RPI group³. Bennhold and Tanabe¹⁹ and Sauermann *et al.*¹⁹ have emphasized coupled-channel approaches. General phenomenology has been reviewed by Knöchlein *et al.*¹⁹.

For polarization observables, the nodal trajectory and its value in illuminating the amplitude structure has been stressed by Saghai, Tabakin and collaborators²⁰.

On the quark model, the works of Koniuk and Isgur¹⁵, Close and Li¹⁵, Weber¹⁵ and Capstick¹⁵ have set the stage for more investigations. In this conference, we have had different approaches of quark model presented by Keister¹⁵, Salme¹⁵, Iachello¹⁵ and Leviatan¹⁵. In particular, questions have been raised as to whether $N^*(1535)$ is a conventional q^3 state²¹. If the answer is no, where is the regular q^3 state with the same quantum numbers? Thus, the processes (1) and (2) should address some of these vital questions.

Whole sets of issues come up in discussing the relationships between η and η' that

we have discussed elsewhere²². These include the chiral U(1) problem²³, the quark contents²⁴ of η , η' , the η_1 - η_8 mixing angle²⁵ and so on. Finally, Leinweber *et al.*² have approached the γNN^* amplitudes on the lattice, while Oka and collaborators²⁶ have compared the πNN^* vs. ηNN^* coupling constants in the QCD sum rules, indicating how the former can be suppressed relative to the latter.

All in all, the subject of $N^*(1535)$ is hot both theoretically and experimentally. At TJNAF, there are experimental proposals pending in *all* Halls of CEBAF.

3 The Effective Lagrangian Approach (ELA)

We have discussed in detail the tree-level ELA in the literature³. We shall quote the main conclusions of these discussions here. First, the pseudoscalar eta-nucleon coupling constant is *not* well-known. One can give a rather broad range for g_η :

$$0.2 \leq g_\eta \leq 6.2. \quad (3)$$

The vector meson sector have effective strong parameters g_i^v given by

$$\begin{aligned} \lambda_\rho g_v^\rho + \lambda_\omega g_v^\omega &= 5.93 \pm 0.82, \\ \lambda_\rho g_t^\rho + \lambda_\omega g_t^\omega &= 17.50 \pm 2.57, \end{aligned} \quad (4)$$

while the electromagnetic decay amplitudes λ_i for the vector mesons controlling the vector meson radiative decay width are

$$\begin{aligned} \lambda_\rho &= 1.06 \pm 0.15, \\ \lambda_\omega &= 0.31 \pm 0.06. \end{aligned} \quad (5)$$

From our earlier experiences, we know the non-resonant Born sectors to be relatively unimportant. The main player is the s-channel excitation of the $N^*(1535)$, followed by some modest importance of the excitation of the $N^*(1520)$. The effective Lagrangian involving the $N^*(1535)$ is discussed here for brevity. It is given by

$$L_{\eta NR}^{ps} = -ig_{\eta NR} \bar{N} R \eta + h.c., \quad (6)$$

$$L_{\gamma NR} = \frac{e}{2(M_R + M)} \bar{R} (k_R^s + k_R^v \tau_3) \gamma_5 \sigma_{\mu\nu} N F^{\mu\nu} + h.c., \quad (7)$$

thereby introducing an effective parameter $\chi_p = k_R^p g_{\eta p R}$, where $k_R^p = k_R^s + k_R^v$ for proton targets and χ_n , an appropriate parameter for neutron, describing the resonance dominated eta photoproduction. For the electroproduction, we study the q^2 dependence of these parameters, which allows us a rigorous test of the QCD-inspired models, and ultimately QCD itself.

For the spin-3/2 (and higher spin) resonances, the effective Lagrangian is more complicated, as we have discussed elsewhere²⁷. The strong interaction Lagrangian, $L_{\eta NR}$, to excite the resonance R , is given by²⁷

$$L_{\eta NR} = \frac{f_{\eta NR}}{\mu} \bar{R}^\mu \theta_{\mu\nu}(Z) \gamma_5 N \partial^\nu \eta + h.c., \quad (8)$$

where the term $\theta_{\mu\nu}(V)$ is given by

$$\theta_{\mu\nu}(V) = g_{\mu\nu} + \left[\frac{1}{2}(1 + 4V)A + V\right] \gamma_\mu \gamma_\nu. \quad (9)$$

The parameter $V(= Z \text{ here})$ is unknown, and has to be fitted as an “off-shell” parameter (two more would come from the photon vertices for real photons), while the “point-transformation” parameter A drops out from observables. The above Lagrangian yields an “off-shell” spin-1/2 sector²⁷, influencing the non-resonant multipoles.

4 Our Results for Real Photons

We first summarize our results for the photoproduction. In Fig.2, we show our beautiful fits of the Mainz angular distribution data off proton at $E_\gamma = 716$ and 790 MeV. In the former, the angular distribution is flat, indicating the dominance of the E_{0+} multipoles, while the latter demonstrates the effects of the higher partial waves.

We can extract from the above fits a nearly model independent electrostrong parameter, related to χ_p and χ_n mentioned earlier³:

$$\xi_i = \sqrt{(\zeta_i \Gamma_\eta)} A_{1/2}^i / \Gamma_T \quad (10)$$

where $i = n, p$, Γ_η and Γ_T are the partial ηN and total widths of the resonance $N^*(1535)$, ζ_i , some kinematic factor ($\zeta_p \approx \zeta_n \approx 1.6$), $A_{1/2}^i$, the photon helicity amplitude. It is this parameter that needs to be computed in QCD.

In Table 2, we summarize our results for the η photoproduction showing the model-independent parameters we have extracted from the data. There is a substantial disagreement with a quark model calculation of these parameters in the approach of Capstick and Roberts¹⁵. This is an urgent worry for the theorists. However, the ratio $A_{1/2}^n / A_{1/2}^p$ is predicted correctly in the quark model: we get

$$A_{1/2}^n / A_{1/2}^p = -0.84 \pm 0.15, \quad (11)$$

and the quark models¹⁵ give -0.83 . In this ratio, the strong interaction physics drops. What does this apparent agreement and the disagreement in Table 2 mean? We need to understand this better.

We shall return to the emerging results on polarization observables in future communications. Suffice to say that the polarization observables will tell us more about the role of $N^*(1520)$ ²⁸.

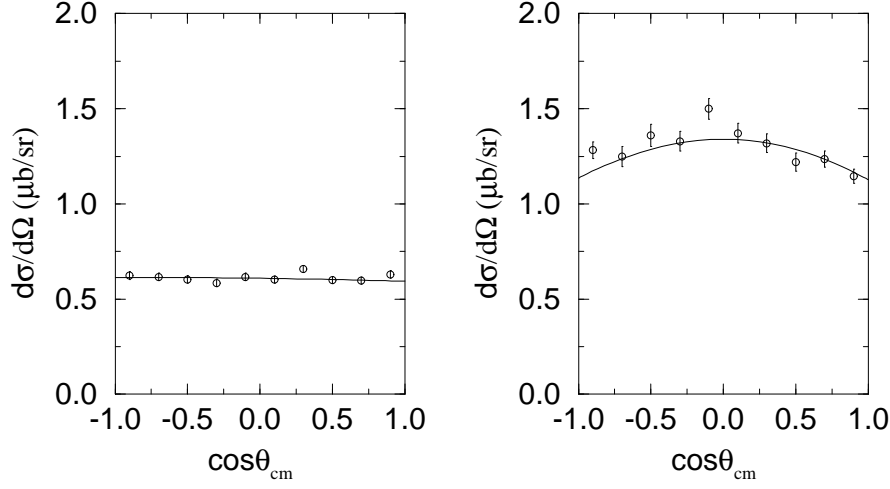


Figure 2. Angular distributions³ at $E_\gamma = 716$ and 790 MeV fitted by our ELA. Data from the Mainz experiment.⁵

Table 2. Proton and neutron electrostrong parameters ξ_p , ξ_n for $N^*(1535)$ excitation and decay via the eta channel. Results are all in units of 10^{-4} MeV^{-1} .

	Our result ³	Quark model ¹⁵
ξ_p	2.20 ± 0.15	1.13
ξ_n	-1.86 ± 0.20	-0.94

5 Our Results for Electroproduction

Here we must make use of the old data base⁹, since precious few new results are in. Our results are best summarized in Fig.3, where we plot the parameter ξ_T , extracted from the existing data, as a function of Q^2 . The important result here is the *utter failure* of the quark model to reproduce this nearly model-independent parameter, extracted from the data by us⁴. This figure, along with Table 2, constitute our main result.

6 Conclusions

Paul Stoler has asked²⁹ a question earlier during this workshop: Would our current effort be written up in the *New York Times*? We know the answer to that one! Nevertheless, something very exciting is happening right before us! For the $N^*(1535)$,

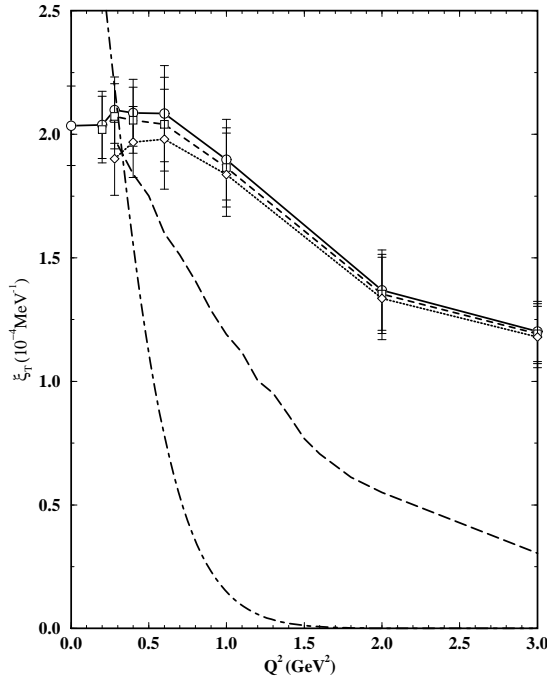


Figure 3. ξ_T vs. Q^2 for different prescriptions⁴ of $S_{1/2}$ to $A_{1/2}$ ratio: (a) set $S_{1/2} = 0$ (circles connected by a solid line); (b) fix $S_{1/2}/A_{1/2}$ by the quark shell model¹⁵ (squares connected by a dashed line); (c) use the value of $S_{1/2}$ from refs. [14, 15, 16] of ref. [29] (diamonds connected by a dotted line). The non-relativistic quark model prediction of ref.15 is the dot-dashed line. The prediction from a light front approach of Stanley and Weber²⁹ is also shown (long-dashed line), with their parameter $\alpha = 0.2 GeV^2$.

there is *an acute shortage of the transition electricity in the quark model*, compared to our observations at the photon point. This shortage becomes even more serious at higher Q^2 . This is akin to the shortage of transition magnetism in the $N \rightarrow \Delta$ transition, where the quark model is also in serious trouble. Thus, *history is being made, as the venerable quark model is failing badly* right before our eyes!

QCD, come and rescue us!

7 Acknowledgments

One of us (NCM) thanks the organizers for the invitation. NCM and MB thank the INT for the wonderful hospitality. NCM has the special pleasure to thank Harry Lee for many stimulating conversations. We thank R. Davidson for many discussions. The research of NCM and JFZ is supported in part by the U.S. Department of Energy. The research of MB is supported by the Natural Sciences and Engineering Research Council of Canada.

1. N. Isgur, this workshop.
2. D. Leinweber, T. Draper and R. M. Woloshyn, *Phys. Rev.* **D46** (1992) 3067.
3. M. Benmerrouche and N. C. Mukhopadhyay, *Phys. Rev. Lett.* **67** (1991) 1070.
M. Benmerrouche, N. C. Mukhopadhyay and J. -F. Zhang, *Phys. Rev.* **D51** (1995) 3237. N. C. Mukhopadhyay, J. -F. Zhang and M. Benmerrouche, *Phys. Rev. Lett.* **75** (1995) 3022; *Phys. Lett.* **B364** (1995) 1.
4. M. Benmerrouche, N. C. Mukhopadhyay and J. -F. Zhang, *Phys. Rev. Lett.* **77** (1996) 4716.
5. B. Krusche *et al.*, *Phys. Rev. Lett.* **74** (1995) 3736; **75**, (1995) 3032; *Phys. Lett.* **B358** (1995) 40. S. Dytman *et al.*, *Phys. Rev.* **C51** (1995) 2170. J. Price, *et al.*, *Phys. rev.* **C51** (1995) R2283. B. Krusche, this workshop.
6. C. A. Heusch *et al.*, *Phys. Rev. Lett.* **25** (1970) 1381.
7. J. -P. Didilez, P. Levi Sandri and M. Ripani, *private communication* (1996).
8. S. Homma *et al.*, *J. Phys. Soc. (Japan)* **57** (1988) 828 and refs. therein.
9. J. C. Alder *et al.*, *Nucl. Phys.* **B91** (1975) 386. F. W. Brasse *et al.*, *Z. Phys.* **C22** (1984) 33 and refs. therein. V. Burkert and L. Elouadrhiri, *this workshop*.
10. R. M. Barnett *et al.*, *Phys. Rev.* **D54** (1996) 1.
11. J. D. Bjorken and S. D. Drell, *Relativistic Quantum Mechanics* (McGrawHill, New York) (1969) 158.
12. E.g., K. Nakayama, *this workshop*.
13. R. M. Davidson and N. C. Mukhopadhyay, *Phys. Rev.* **D42** (1990) 20. R. M. Davidson, N. C. Mukhopadhyay and R. Wittman, *Phys. Rev.* **D43** (1991) 71.
14. R. Beck, *this workshop*.
15. R. Koniuk and N. Isgur, *Phys. Rev.* **D21** (1980) 1868. M. Warns *et al.*, *Z. Phys.* **C45** (1990) 613. W. Konen and H. J. Weber, *Phys. Rev.* **D41** (1990) 2201. S. Capstick and W. Roberts, *Phys. Rev.* **D49** (1994) 4570. L. Ya. Glozman and D. O. Riska, *Phys. Rep.* **268** (1996) 263. Z. Li, A. Leviatan, F. Iachello, L. Glozman, B. Keister and G. Salme, *this workshop*.
16. N. C. Mukhopadhyay, A. Nathan and L. Zhang, *Phys. Rev.* **D47** (1993) R7.
17. C. E. Carlson and N.C. Mukhopadhyay, *Phys. Rev. Lett.* **74** (1995) 1288.
18. M. Wilhelm, *Ph.D thesis* (Bonn) (1993).
19. C. Bennhold and H. Tanabe, *Nucl. Phys.* **A530** (1991) 625. C. Sauermann *et al.*, *Phys. Lett.* **B341** (1995) 261. G. Knöchlein, D. Drechsel and L. Tiator, *Z. Phys.* **A352** (1995) 327.
20. B. Saghai and F. Tabakin, *nucl-th/9606042* (1996).
21. R. Bijker *et al.*, *nucl-th/9608057*. N. Kaiser, P. B. Siegel and W. Weise, *Phys. Lett.* **B362** (1995) 23.
22. J. -F. Zhang, N. C. Mukhopadhyay and M. Benmerrouche, *Phys. Rev.* **C52** (1995) 1134. N. C. Mukhopadhyay, J. -F. Zhang and M. Benmerrouche, *Las Cruces Workshop* (1996).
23. S. Weinberg, *Phys. Rev.* **D11** (1975) 3583. G. 't Hooft, *Phys. Rev.* **C37** (1976)

8.

- 24. R. Baltrusaitis *et al.*, *Phys. Rev.* **D32** (1985) 2823.
- 25. F. Lenz, *Nucl. Phys.* **B279** (1987) 119.
- 26. M. Oka, *this workshop*. D. Jido *et al.*, *hep-ph/9610520*.
- 27. M. Benmerrouche, R. M. Davidson and N. C. Mukhopadhyay, *Phys. Rev.* **C39** (1989) 2339.
- 28. J. W. Hyun and N. Mathur, *private communication* (1996) [they are students from the RPI undergraduate and graduate program respectively].
- 29. R. H. Stanley and H. J. Weber, *Phys. Rev.* **C52** (1995) 435.
- 30. P. Stoler, *this workshop*.